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RESEARCH ARTICLE

## Spatio-temporal variations in organic carbon density and carbon sequestration potential in the topsoil of Hebei Province, China

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### Abstract

Reliable prediction of soil organic carbon (SOC) density and carbon sequestration potential (CSP) plays an important role in the atmospheric carbon dioxide budget. This study evaluated temporal and spatial variation of topsoil SOC density and CSP of 21 soil groups across Hebei Province, China, using data collected during the second national soil survey in the 1980s and during the recent soil inventory in 2010. The CSP can be estimated by the method that the saturated SOC content subtracts the actual SOC associated with clay and silt. Overall, the SOC density and CSP of most soil groups increased from the 1980s to 2010 and varied between different soil groups. Among all soil groups, Haplic phaeozems had the highest SOC density and Endogleyic solonchaks had the largest CSP. Areas of soil groups with the highest SOC density (90 to 120 t C ha<sup>-1</sup>) and carbon sequestration (120 to 160 t C ha<sup>-1</sup>) also increased over time. With regard to spatial distribution, the north of the province had higher SOC density but lower CSP than the south. With respect to land-use type, cultivated soils had lower SOC density but higher CSP than uncultivated soils. In addition, SOC density and CSP were influenced by soil physicochemical properties, climate and terrain and were most strongly correlated with soil humic acid concentration. The results suggest that soil groups (uncultivated soils) of higher SOC density have greater risk of carbon dioxide emission and that management should be aimed at maximizing carbon sequestration in soil groups (cultivated soils) with greater CSP. Furthermore, soils should be managed according to their spatial distributions of SOC density and carbon sequestration potential under different soil groups.

**Keywords:** carbon sequestration, SOC density, spatial variation, topsoil

## 1. Introduction

Terrestrial soil play an important role in the atmospheric carbon dioxide budget. Soils contain 1 500 Pg of organic carbon (Batjes 1996), which is 2.5 to 3 times the amount of organic carbon found in the global atmosphere or in terrestrial vegetation (Liu *et al.* 2006). The upper soil layer directly interacts with the atmosphere and is sensitive to land-use conversion, deforestation and human disturbances (Gao

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*et al.* 2008). Therefore, estimating the soil organic carbon (SOC) density and carbon sequestration potential (CSP) in topsoil is important for understanding the soil carbon dynamics in different soil groups and regions. Furthermore, these estimates will help establish better soil management practices to improve soil quality and mitigate the effects of global warming.

Recently, national- and regional-scale SOC density and carbon sequestration research has attracted considerable attention, particularly for agricultural soils (Jobbágy and Jackson 2000). Numerous studies have been conducted to estimate agricultural soil carbon sequestration potentials and explore management options to enhance carbon sequestration at national and regional levels (Vleeshouwers and Verhagen 2002; Marland *et al.* 2003; Dendoncker *et al.* 2004). In China, several studies have focused on SOC, including SOC analyses related to soil type and vegetation and preliminary assessments of the effects of cultivation and land use on SOC concentration (Chen *et al.* 2007; Yu *et al.* 2009; Fu *et al.* 2010).

Various methods have been developed to estimate SOC density and CSP (Xu *et al.* 2011; Olson *et al.* 2014a; Olson *et al.* 2014b). Traditionally, SOC density has been calculated from a given SOC content and bulk density (Wang S *et al.* 2004; Wang W *et al.* 2004), whereas the CSP has been calculated from carbon saturation levels associated with the contents of clay, silt and SOC (Hassink 1997; Angers *et al.* 2011). In recent decades, models have been developed to estimate SOC density and CSP. For example, the denitrification-decomposition (DNDC) model was employed to explore effective carbon sequestration options at regional and national scales using a regional mode (Li *et al.* 2004; Tang *et al.* 2006; Zhang *et al.* 2006). In addition, a site-level, process-based model has been linked with a geographic information system (GIS) to extrapolate point measurements at regional scales (Falloon *et al.* 2000; Zimmerman *et al.* 2004). However, soil carbon sequestration is a complex process that is influenced by many factors, such as organic carbon inputs from crop residues or organic manure applications, climatic factors, soil properties, original carbon level and soil type (Wang S *et al.* 2004; Wang W *et al.* 2004). These factors can result in uncertainties when performing estimations using simple scaled-up point measurements, which are used in the model.

In this study, we evaluated the SOC density and CSPs of soils from different groups in Hebei Province, China, based on historical and current basic soil data sets that were collected during the second national soil survey (Wei 1987) conducted in the 1980s and the most recent soil survey conducted in 2010. The objectives of this study were to: (1) estimate the temporal and spatial variations of the SOC density and CSP in topsoil in Hebei Province; and (2)

identify the factors influencing potential variations in SOC density and carbon sequestration.

## 2. Materials and methods

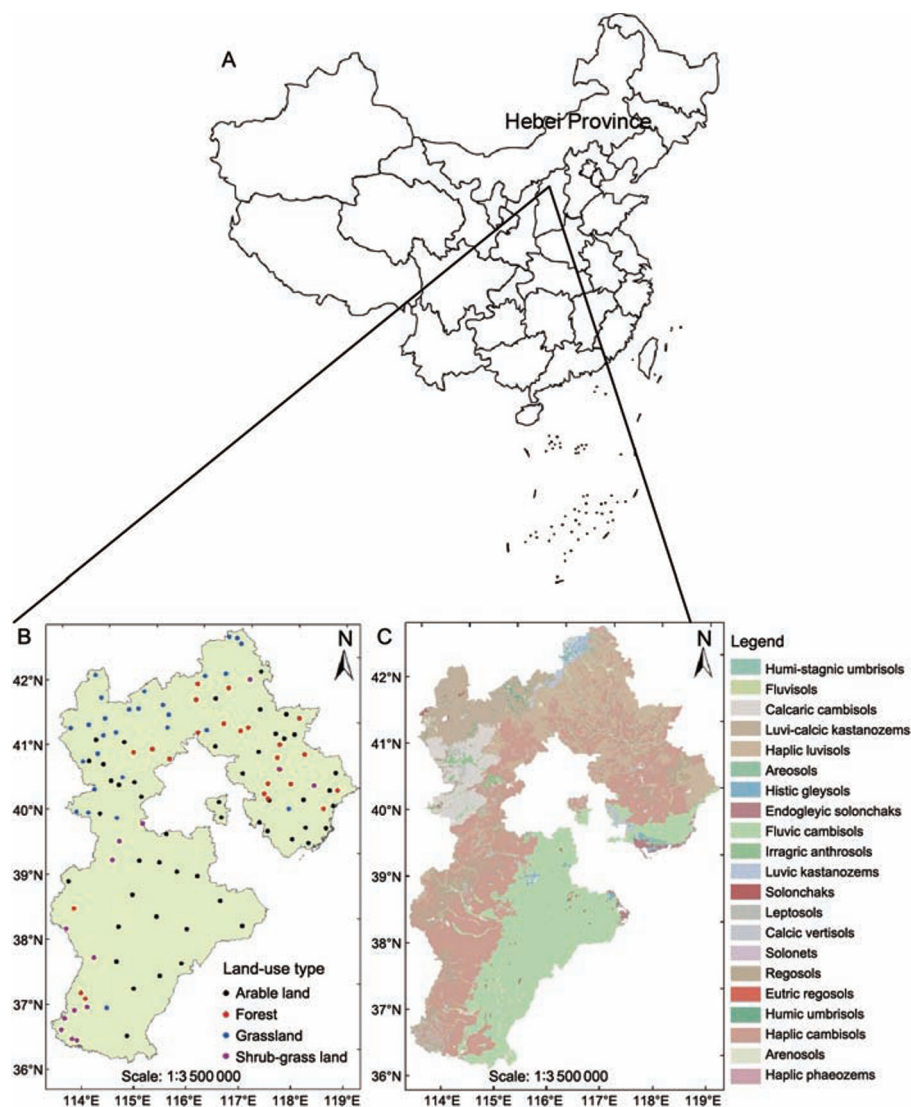
### 2.1. Study area

This study was conducted in Hebei Province (36°–43°N, 113°–120°E) in northern China, which encompasses a total area of 190 000 km<sup>2</sup>. Of this area, 40% consists of arable land. Elevations in Hebei Province range from >1 000 m in the highland north to <50 m in the lowland south, and the province borders the Taihang Mountains to the west and the Bohai Sea to the east. Furthermore, Hebei Province has a warm temperate continental monsoon climate with cold and dry winters and hot and humid summers. The average air temperatures in this region are –16 to –3°C in January and 20 to 27°C in July, and the annual precipitation ranges from 400 to 800 mm and are heavily concentrated during the summer. The abundant geographic and climatic variations in the region have created diverse soil properties, which make the province an ideal region for studying soil carbon storage in various soil groups. According to the soil classification system of the world reference base for soil resources (<http://www.fao.org/docrep/003/y1899e/y1899e03.htm>), the entire province has 21 dominant soil groups (Fig. 1), and the area of each soil group ranged from 9 to 51 000 km<sup>2</sup> (Table 1).

### 2.2. Data sources

We used relevant databases and maps from soil samples collected during the second national soil survey of China (Wei 1987) in the 1980s to evaluate historical soil carbon storage. The Hebei Province soil database contains information from 120 soil profiles that cover the 21 soil types found in the province (Zhong and Zhao 2001). And each site was a depositional site. The soil profile information includes the geographic location, soil depth, organic matter content, vegetation, land-use pattern and bulk density of the soil profiles. This information provides an important framework for analyzing the soil carbon storage of each soil group.

To evaluate the current soil carbon storage and compare it with historical values, 120 soil profiles from across Hebei Province were sampled again in 2010 according to the plot names in *Soil in Hebei* (Wei 1987). These sites were dispersed across the 21 soil groups and selected using a soil, land-use, geological, and geomorphological map (1:250 000). The northern portion of the province was more intensively sampled than the southern portion because of its diverse elevations and soil groups (Fig. 1). The geographical coordinates of the sampling locations were recorded



**Fig. 1** The land-use map, soil sample and soil map of study area. A, location of Hebei Province, China. B, a land-use map of Hebei Province and the distribution of soil sample sites in 2010. C, a soil map showing the dominant soil groups.

using a global positioning system (GPS).

Soil samples were air-dried, ground and passed through a 2-mm sieve. The SOC content was determined using the rapid dichromate oxidation method on the smallest size fraction of the sieved (0.25 mm) samples (Bao 2000). The soil bulk density was determined using the core method, oven-dried soil mass and sampled field volume (Liu 1982). The soil particle size was determined using a laser particle size analyzer (Liu *et al.* 2006). The total N contents were analyzed using the Kjeldahl method (McGill and Figueiredo 1993), and the fresh soil pH was measured using a pH meter. Humic acid and amorphous iron were determined using the sodium pyrophosphate extraction-potassium dichromate and phenanthroline colorimetry methods, respectively (Lu 2000).

### 2.3. Calculation methods

**Calculation of the SOC density in topsoil** This study focused on the SOC at a soil depth of 0–30 cm. The reason is that the upper soil layer directly interacts with the atmosphere and is most vulnerable to land-use conversion, deforestation and human disturbances. The topsoil SOC density ( $D_{\text{soc}}$ ) was estimated using eq. (1) (Schwager and Mikhailova 2002):

$$D_{\text{soc}} = \text{SOC}_{0-30 \text{ cm}} \times \gamma \times H \times (1 - d_{2\text{-mm}}/100) \times 10^{-1} \quad (1)$$

Where,  $\gamma$  ( $\text{g cm}^{-3}$ ) is the bulk density,  $H$  is the soil depth (30 cm), and  $d_{2\text{-mm}}$  (%) is the 2-mm coarse fraction of the soil.

**Calculation of the carbon sequestration potential** The saturated SOC content can be estimated based on the soil's clay content because a positive relationship is observed

**Table 1** Total areas of different soil groups and soil organic carbon (SOC) densities in the 1980s and 2010, and the change rate of mean annual SOC density in each soil from the 1980s to 2010

Soil group	Area (ha)	1980s	2010	Rate of change (t C yr <sup>-1</sup> )
		SOC density (t C ha <sup>-1</sup> )	SOC density (t C ha <sup>-1</sup> )	
Luvi-calci kastanozems	1 277 351	47.75	61.29	0.451
Haplic luvisols	2 308 508	76.85	52.99	-0.795
Humic umbrisols	69 982	85.61	56.24	-0.979
Histic gleysols	71 047	30.84	49.62	0.626
Leptosols	386 345	52.32	70.12	0.593
Haplic phaeozems	1 559	101.05	85.65	-0.513
Regosols	1 451 576	25.17	48.23	0.769
Arenosols	182 847	2.42	22.25	0.661
Calcic vertisols	65 447	44.39	46.63	0.075
Solonets	81 693	25.75	65.25	1.317
Solonchaks	952 293	11.96	34.26	0.743
Irragic anthrosols	84 450	32.02	34.55	0.084
Fluvisols	74 466	4.90	36.54	1.055
Calcaric cambisols	734 978	25.26	31.95	0.223
Haplic cambisols	5 080 395	32.54	37.09	0.152
Fluvic cambisols	4 251 113	41.92	33.59	-0.278
Eutric regosols	867	9.16	34.23	0.836
Anthrosols	48 976	36.94	42.66	0.191
Endogleyic solonchaks	203 301	26.42	22.86	-0.119
Luvic kastanozems	105 515	67.49	72.84	0.178
Humi-stagnic umbrisols	43 197	81.11	70.85	-0.342

between SOC stabilization and the soil clay or clay plus silt content (Hassink 1997), which is related to the binding of organic material to the reactive surfaces of clayey particles. A fine-textured soil with a greater reactive surface area often has a higher carbon-to-clay particle binding rate than a coarse-textured soil. Therefore, the maximum (max.) saturated SOC ( $C_{\text{sat}}$ , g kg<sup>-1</sup>) associated with clay and silt particles (<20  $\mu\text{m}$ ) was calculated as follows (Hassink 1997):

$$C_{\text{sat}} = 4.09 + 0.37 \times (\text{clay} + \text{silt})\% \times 100 \quad (2)$$

Thus, the amount of SOC which can potentially be sequestered ( $S_{\text{def}}$ , g kg<sup>-1</sup>) was calculated as follows (Angers *et al.* 2011):

$$S_{\text{def}} = C_{\text{sat}} - x \text{SOC}_{0-30 \text{ cm}} \quad (3)$$

Where,  $x$  is the proportion of SOC associated with clay and silt (<20  $\mu\text{m}$ ) in the total  $\text{SOC}_{0-30 \text{ cm}}$ . This value ranges from 85 to 89% and is generally  $(85 \pm 2.5)\%$ .

Finally, the carbon sequestration potential (CSP, t C ha<sup>-1</sup>) was estimated using eq. (4):

$$\text{CSP} = S_{\text{def}} \times \gamma \times H \times (1 - d_{2\text{-mm}}/100) \times 10^{-1} \quad (4)$$

**Calculation of the soil bulk density** The soil bulk density was measured for only 30 topsoil samples in the second national soil survey (Wei 1987) and the current soil survey in 2010 in China. Thus, the bulk density of the remaining soil samples was estimated based on the regression between the measured bulk density ( $\gamma$ , g cm<sup>-3</sup>) and the SOC content (Pan *et al.* 2004), which was calculated as follows (Fig. 2):

$$\gamma = 1.5915 \times e^{-0.012 \text{SOC}} \quad (5)$$

## 2.4. Statistical analysis

The data were analyzed using SPSS 17.0 and GS+7.0. A one-way ANOVA was used to test for significant differences in soil properties among the soil groups using a significance level of  $P < 0.05$ . A paired  $t$ -test was used to test for significant differences between the samples collected in the 1980s and in 2010. A correlation analysis was performed to identify the factors that influence SOC. The dependent variables were SOC content and CSP, and the independent variable was soil type. The spatial distributions of SOC density and CSP were analyzed using the ordinary Kriging method.

## 2.5. Accuracy assessment

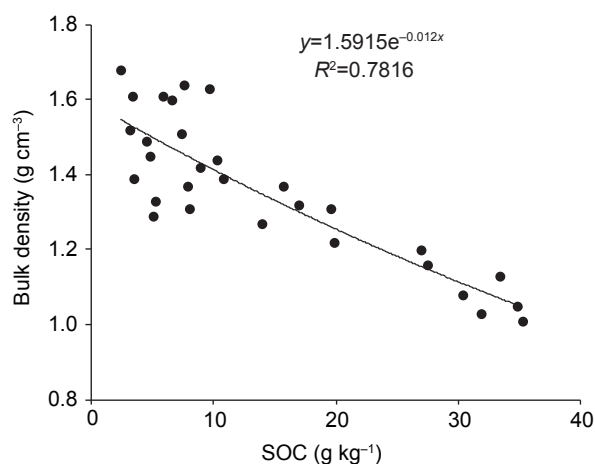
An independent validation method was used to assess the accuracy of the spatial predictions (Alsamamra *et al.* 2009). Overall, 20 of the 120 SOC sampling sites were used as validation points; the remaining points were used for the interpolation. The mean prediction error (ME) and root-mean-square prediction error (RMSE) were used to evaluate the predictive accuracy as follows:

$$\text{RMSE} = \frac{1}{n} \sum_{i=1}^n [Z(x_i) - Z^*(x_i)] \quad (6)$$

$$\text{RMSE} = \sqrt{\frac{1}{n} \sum_{i=1}^n [Z(x_i) - Z^*(x_i)]^2} \quad (7)$$

Where,  $n$  is the number of validation points, and  $Z(x_i)$  and





**Fig. 2** The correlation of bulk density and soil organic carbon.

$Z^*(x_i)$  are the measured and predicted values, respectively. Lower ME and RMSE values correspond to more accurate prediction results.

### 3. Results and discussion

#### 3.1. Changes in the soil organic carbon density in different soils from the 1980s to 2010

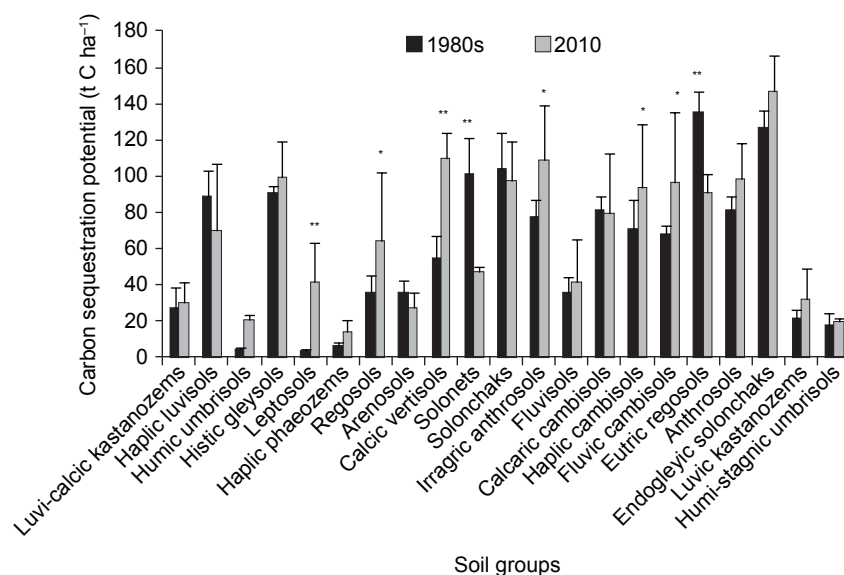
The SOC densities of the different soil groups are shown in Table 1. During the 1980s, the highest mean SOC densities were observed in Haplic phaeozems ( $101.05 \text{ t C ha}^{-1}$ ), and the lowest mean SOC densities were observed in Arenosols ( $22.25 \text{ t C ha}^{-1}$ ).

Despite the substantial decreases and increases in SOC densities in the Haplic phaeozems ( $85.65 \text{ t C ha}^{-1}$ ) and Arenosols ( $22.25 \text{ t C ha}^{-1}$ ), respectively, over the 30-year study period, the two soil groups featured the highest and lowest SOC densities, respectively, among all of the soil types in 2010.

From the 1980s to 2010, SOC density increased in most soils except for the Haplic luvisols, Humic umbrisols, Haplic phaeozems, Fluviic cambisols, Endogleyic solonchaks and Humi-stagnic umbrisols, which exhibited decreased SOC density. The rates of change of these six soils were  $-0.795$ ,  $-0.979$ ,  $-0.513$ ,  $-0.278$ ,  $-0.119$  and  $-0.342 \text{ t C yr}^{-1}$ , respectively. The decreasing SOC density rates of the Haplic phaeozems were similar to those reported by Yu *et al.* (2004), who attributed these values to reclamation and water erosion. Batjes (1996) reported that the worldwide mean topsoil (0–30 cm) SOC densities of Arenosols and Luvisols were 13 and  $51 \text{ t C ha}^{-1}$ , respectively. Thus, the SOC densities of the Arenosol and Haplic luvisol topsoil in Hebei were comparable to or slightly higher than the global average.

#### 3.2. Comparison of the carbon sequestration potentials of different soil groups observed in the 1980s and 2010

CSP significantly changed between the 1980s and 2010 (Fig. 3). In most of the soils, CSP increased. However, CSP decreased in the Haplic luvisols, Solonchaks, Solonchaks, Calcaric cambisols and Eutric regosols. During the 1980s,



**Fig. 3** Mean values (with standard errors) of the carbon sequestration potential in different soil groups in the 1980s and 2010. Significant changes in the carbon sequestration potential between the 1980s and 2010 were determined according to paired *t*-tests. \* represents significant difference at  $P < 0.05$  and \*\* represents significant difference at  $P < 0.01$ .

CSP values ranged from  $(4.54 \pm 1.23) \text{ t C ha}^{-1}$  in the Leptosols to  $(135.47 \pm 11.47) \text{ t C ha}^{-1}$  in the Eutric regosols. In 2010, CSP values ranged from  $(14.03 \pm 3.25) \text{ t C ha}^{-1}$  in the Haplic phaeozems to  $(146.91 \pm 19.43) \text{ t C ha}^{-1}$  in the Endogleyic solonchaks (Fig. 3).

From the 1980s to 2010, CSP significantly increased in the Leptosols (10.24 times), Regosols (0.78 times), Calcic vertisols (0.99 times), Irragic anthrosols (0.41 times), Haplic cambisols (0.31 times) and Fluvic cambisols (0.41 times), whereas it significantly decreased in the Solonets (0.53 times) and Eutric regosols (0.33 times). All of the remaining soils did not exhibit significant changes in carbon sequestration from the 1980s to 2010 (Fig. 3).

### 3.3. Spatial SOC density and CSP variations in the 1980s and 2010

**Classic statistical characteristics and the normal distribution test** The results of the statistical analyses of SOC density and CSP are shown in Table 2. The mean SOC density and CSP values were similar to the median values, which suggest that the SOC density and CSP distributions were relatively uniform in some areas. The coefficient of variation (CV) values for SOC density and carbon sequestration were greater than 1, indicating large spatial variations in SOC density and CSP. Thus, the SOC density and CSP of the study area satisfied the statistical hypothesis. The results of the Kolmogorov-Smirnov (K-S) test along with the relatively low Skew and Kurtosis values suggest that the SOC density and CSP values conformed to a normal distribution, which is supported by spatial analyses using geostatistical methods.

**Analysis of the semi-variance function** Our SOC density and CSP variability analyses were based on the selection

of a semi-variogram. The SOC density and CSP values were analyzed using GS+7.0, and optimal semi-variogram fitting models were selected by comparing the nugget, sill, nugget coefficient and determination coefficient (Table 3, Fig. 4). The heterogeneities of the SOC densities and CSPs were affected by structural and random factors. Structural factors, such as climatic parameters, parent material, terrain and soil type, can strengthen spatial correlations. In contrast, random factors, such as fertilization, tillage and planting systems, can weaken spatial correlations. The nugget coefficient represents the degree of spatial variability in the model of the semi-variance function. A small nugget coefficient suggests that the spatial variability is caused by structural factors rather than random factors, whereas a large nugget coefficient suggests the opposite. The nugget coefficients of SOC density and CSP were 40% (greater than 25%) and 24.2% (less than 25%) in the 1980s, respectively. These values suggest that the SOC density exhibited medium spatial correlation strength and indicate that the CSP exhibited strong spatial correlations with structural factors. In 2010, the nugget coefficients of SOC density and CSP were 2.6 and 0.1% (less than 25%), respectively, and both exhibited strong spatial correlations with structural factors.

**Spatial distribution characteristics of the SOC density and CSP** The spatial patterns of SOC density and CSP have been illustrated for different soil groups in Hebei, China (Fig. 5). In the 1980s, SOC density increased from 0–30  $\text{t C ha}^{-1}$  (12.7% of total land area) in the southeast to 90–120  $\text{t C ha}^{-1}$  (4.1% of the total land area) in the northwest. The main soil groups with the lowest SOC densities were Arenosols, Fluvisols, Eutric regosols, Solonchaks, Regosols, Calcic cambisols and Anthrosols, whereas the major soil groups with the highest SOC densities were Humic umbrisols and Haplic phaeozems. Conversely, CSP generally followed

**Table 2** Summary statistics for SOC density and carbon sequestration potential

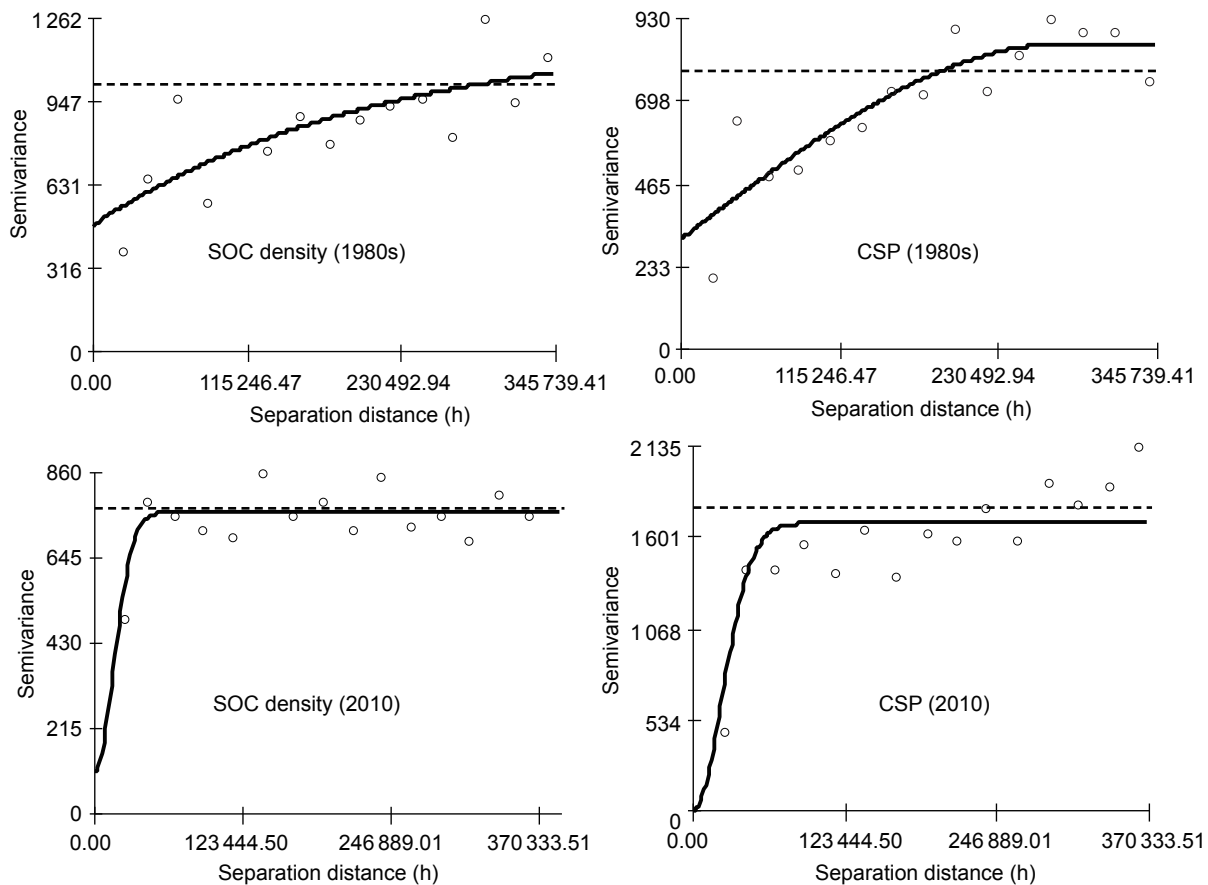
Item <sup>1)</sup>	Year	Number of samples	Statistics ( $\text{t C ha}^{-1}$ )					CV <sup>2)</sup>	Skewness	Kurtosis	K-S testing
			Minimum value	Maximum value	Mean value	Standard deviation	Median value				
CSP	1980s	100	1.39	110.06	44.37	27.93	40.88	1.58	0.62	−0.15	Normal
	2010	100	2.35	146.91	74.82	42.11	70.79	1.77	0.11	0.78	Normal
SOC density	1980s	100	5.42	155.06	54.49	31.81	46.45	1.71	−0.76	0.94	Normal
	2010	100	3.95	108.53	44.39	27.46	40.96	1.61	0.52	−0.78	Normal

<sup>1)</sup> CSP, carbon sequestration potential; SOC, soil organic carbon. The same as below.

<sup>2)</sup> CV, coefficient of variation.

**Table 3** Theoretical semi-variogram models and related SOC density and carbon sequestration potential parameters

Item	Year	Theoretical model	Nugget	Sill	Nugget coefficient (%)	Range (km)	R <sup>2</sup>
CSP	1980s	Spherical	206	860	24.2	279	0.776
	2010	Gaussian	1	1 650	0.1	63	0.801
SOC density	1980s	Exponential	478	1 196	40.0	637	0.598
	2010	Gaussian	20	761	2.6	38	0.724



**Fig. 4** Isotropic variability in soil organic carbon (SOC) density and carbon sequestration potential (CSP) in the 1980s and in 2010.

a trend opposite to that of the spatial SOC density trend. CSP increased from 0–40 t C ha<sup>-1</sup> (16.6% of the total land area) in the north and northwest to 120–160 t C ha<sup>-1</sup> (2.1% of the total land area) in the southeast. The major soil groups with the lowest CSP values were Leptosols, Humic umbrisols, Haplic phaeozems, Humi-stagnic umbrisols, Luvic kastanozems, Luvi-calciic kastanozems, Arenosols, Regosols and Fluvisols, whereas the soil groups with the highest CSP values were Solonets, Solonchaks, Endogleyic solonchaks and Eutric regosols.

From the 1980s to 2010, areas with the highest and lowest SOC densities exhibited increasing trends. However, only the areas with the highest CSP values were compared with areas with the highest SOC densities. In 2010, the SOC densities in the northern part of the province were generally higher than those in the south. The SOC densities ranged from 0–30 t C ha<sup>-1</sup> (21.3% of total soil area) in the Irragric Anthrosols, Solonchaks, Eutric regosols and Calcaric cambisols to 90–120 t C ha<sup>-1</sup> (20.6% of total soil area) in the Haplic phaeozems and Fluviic cambisols. The CSP values exhibited an approximately opposite spatial pattern relative to the SOC densities in 2010, similar to the

trend from the 1980s. The northern region of the province exhibited a greater CSP relative to the southern region. The CSP values ranged from 0–40 t C ha<sup>-1</sup> (19.3% of total soil area) in the Luvic Kastanozems, Luvi-calciic kastanozems, Humi-stagnic umbrisols and Haplic phaeozems to 120–160 t C ha<sup>-1</sup> (18.6% of total soil area) in the Irragric anthrosols, Calciic vertisols and Endogleyic solonchaks.

**Accuracy assessment of spatial prediction results** The statistical results from our accuracy assessment of validation site spatial predictions are shown in Table 4 and Fig. 6. The values of ME and RMSE of SOC density and carbon sequestration potential were small in the 1980s and 2010. Compared with 2010, the prediction result of the 1980s was more accurate for carbon sequestration potential. However, the prediction result of 2010 was more accurate than that of the 1980s for SOC density. From the perspective of determination coefficient ( $R^2$ ), the value of carbon sequestration potential in the 1980s (0.755) and 2010 (0.746) and SOC density in 2010 (0.898) was relatively large. However, the value of SOC density in the 1980s (0.412) was small. In general, the prediction result was relatively accurate.

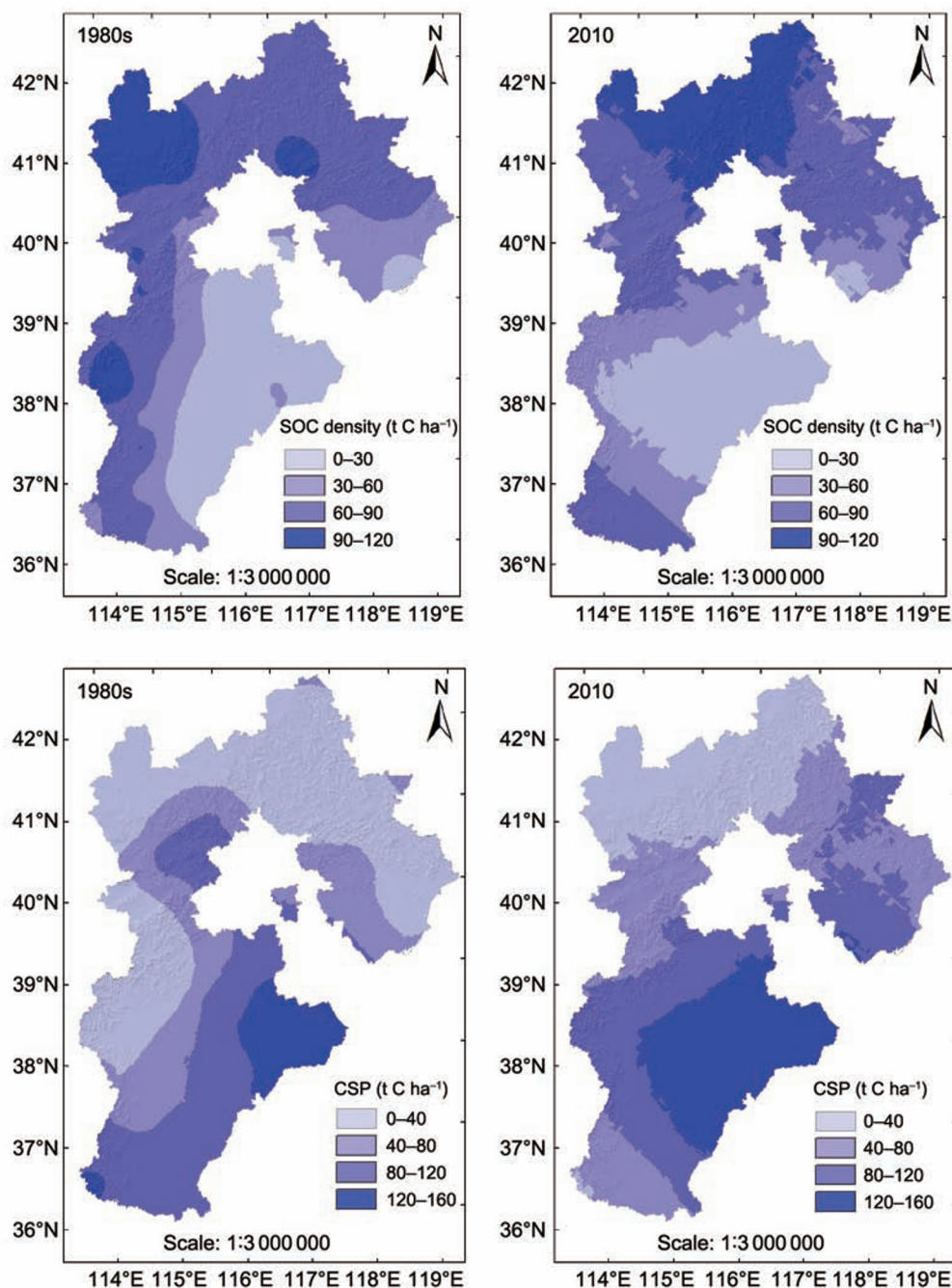


Fig. 5 Spatial distributions of SOC density and carbon sequestration potential in the 1980s and 2010.

### 3.4. Factors influencing SOC and CSP variation

As indicated in Table 5, three principal factors govern SOC content: (1) soil properties, (2) climate and (3) terrain (Li *et al.* 2005; Sun *et al.* 2010). A Pearson correlation analysis was performed (Table 5), and the topsoil organic carbon density was found to be significantly and positively correlated with humic acid and total N and negatively and insignificantly correlated with the gradient. Strong negative correlations

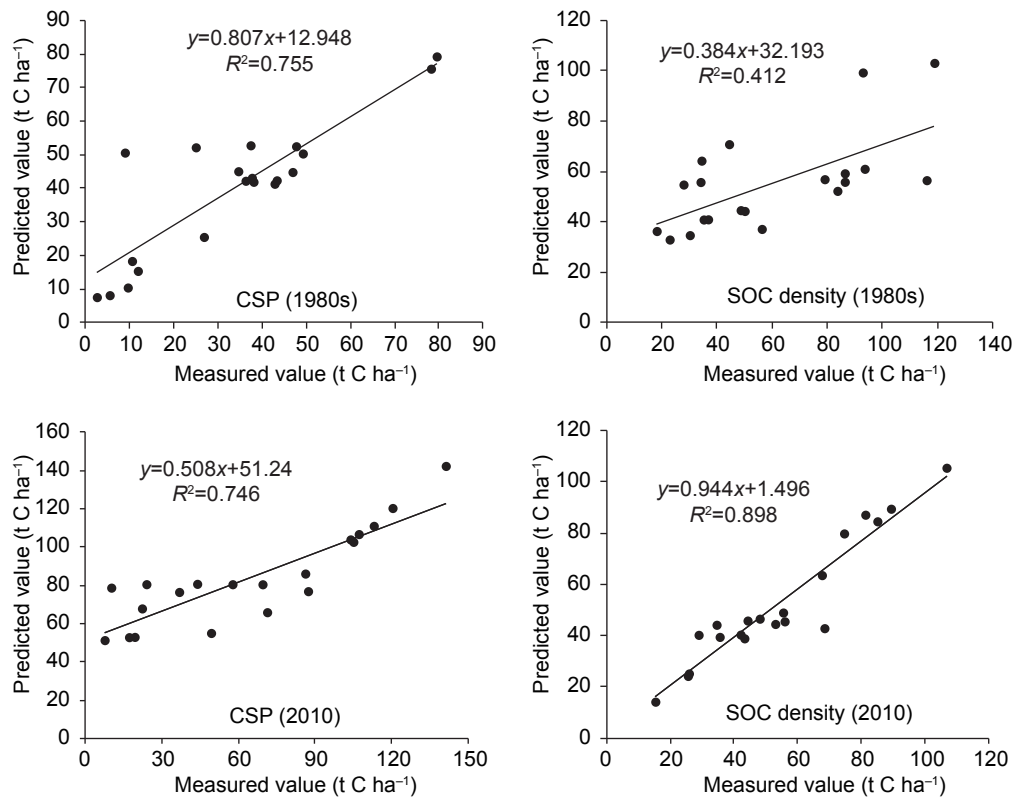
were observed between SOC density and temperature, pH and precipitation. However, CSP exhibited an inverse relationship with SOC. The correlation analysis results also revealed the spatial distribution characteristics of SOC density and CSP. For example, northern Hebei is characterized by higher elevations and lower temperatures than southern Hebei. Consequently, the SOC densities were higher in the north than in the south because microbial activity was lower in the former as a result of the lower temperatures, which



**Table 4** Accuracy assessment of the predicted SOC density and carbon sequestration potential from validation sites

Item	1980s <sup>1)</sup>			2010		
	ME	RMSE	R <sup>2</sup>	ME	RMSE	R <sup>2</sup>
CSP	−2.47	7.43	0.755	−3.96	9.86	0.714
SOC density	4.65	14.21	0.412	−0.80	6.12	0.738

<sup>1)</sup>ME, mean prediction error; RMSE, root-mean-square prediction error.

**Fig. 6** Scatter plots of the measured and estimated SOC density and carbon sequestration potential from validation sites.**Table 5** Pearson correlation coefficients between SOC density or carbon sequestration potential (CSP) and soil properties, climate variables or terrain

Independent variables	SOC density		CSP	
	Pearson correlation	P-value	Pearson correlation	P-value
Humic acid	0.989 <sup>**</sup>	0.000	−0.737 <sup>**</sup>	0.000
Amorphous iron	−0.047	0.776	−0.049	0.794
Total N	0.985 <sup>**</sup>	0.000	−0.715 <sup>**</sup>	0.000
pH	−0.529 <sup>**</sup>	0.000	0.251	0.174
Temperature	−0.348 <sup>**</sup>	0.008	0.351 <sup>*</sup>	0.014
Precipitation	−0.313 <sup>*</sup>	0.017	0.637 <sup>**</sup>	0.000
Gradient	−0.197	0.138	0.080	0.591

<sup>\*</sup> indicates a significant correlation at  $P < 0.05$  (2-tailed) and <sup>\*\*</sup> indicates a significant correlation at  $P < 0.01$  (2-tailed).

allowed for greater accumulation of SOC. The important influence of climate on soil organic matter (SOM) has been reported in a number of studies (Conant *et al.* 2011; Wiesmeier *et al.* 2013). Moreover, vegetation has been shown to have an important influence on the spatial pattern of SOC

density. The influence of vegetation with a high resistance to microbial degradation also contributes to the retardation of SOM decomposition (Hobbie *et al.* 2000; Djukic *et al.* 2010).

SOC density and CSP varied among various land-use types and soil textures (Tables 6 and 7). Arable soils typical-

ly exhibited lower SOC densities than soils with natural uses (forestland, grassland and shrubland-grassland). However, these differences were not significant at the 0.05 confidence level. Tiessen and Stewart (1983) observed that cultivation reduced the soil carbon content associated with silt and clay particles, and Hassink (1997) found that grassland soils had considerable amounts of carbon associated with silt and clay particles. Tillage of arable land enhances soil organic matter decomposition by disturbing the silt- and clay-protected carbon pool; thus, the decay of SOM in cultivated soils is several times higher than that in natural-use lands (Six *et al.* 1998; Balesdent *et al.* 2000). Forestland, grassland and shrubland-grassland soils exhibited higher carbon inputs relative to arable soils. In addition, arable lands exhibited significantly higher CSP values relative to natural soils at a 0.05 level. This result may have occurred because arable soils usually receive lower C input and are tilled which result in lower SOC content and greater potential for further sequestration due to greater saturation deficit (Cotrufo *et al.* 1998; Six *et al.* 2001). From the perspective of soil texture, the difference of SOC densities and CSP was significant in different soil textures. SOC density of loam was the highest and SOC density of loamy sand was the lowest. And CSP of loamy sand was the lowest and CSP of silt-clay loam was the highest. In addition to silt-clay loam, CSP of silt loam and clay loam were also higher (Table 7). This indicated that the potential of carbon sequestration of soil with higher clay and silt content was greater (Hassink 1997).

In addition to soil properties, environment and land-use change, potential future management practices are also the important factors influencing the carbon sequestration potential in continuously cropped soils *via* fertilization, ma-

nure, phytolith and residue management practices (Song 2014a, b). Enhancing nutrient and water use efficiencies can improve soil characteristics and microbial activity, thereby increasing the carbon sequestration potential (Follett 2001). It also may further enhance the cropland phytolith C sequestration and thereby mitigate climate change (Song 2014a, b). The application of biochar from crop residues, which do not have any other economic uses, is one important strategy for enhancing soil carbon sequestration capacities. When applied to soil, biochar produces a range of environmental benefits, including enhanced soil C sequestration potential and improvements in soil fertility (Lehmann 2007; Mishra *et al.* 2010; Srinivasarao *et al.* 2014).

## 4. Conclusion

In Hebei Province, the SOC densities and CSPs of most of the soil groups increased between the 1980s and 2010, and they differed greatly among the soil groups. For example, Haplic phaeozems had the highest SOC densities and Endogleyic solonchaks exhibited the highest CSP values among the studied soil groups. The spatial distribution of SOC density was higher in northern Hebei, and the distribution of CSP was higher in southern Hebei. From the 1980s to 2010, the areas with SOC densities ranging from 90 to 120 t C ha<sup>-1</sup> and CSPs ranging from 120 to 160 t C ha<sup>-1</sup> increased. From a land-use perspective, the SOC density of the cultivated soils was lower than that of the uncultivated soils, and the CSP of the cultivated soils was greater than that of the uncultivated soils. The SOC densities and CSPs were influenced by multiple factors, including the physicochemical properties of the soil, climate and terrain. Humic acid was the most important factor that influenced SOC density and CSP. Thus, the soil groups with lower SOC densities may have a greater potential for carbon sequestration under cultivation. However, soils should be managed according to the spatial distribution patterns of their SOC densities and CSPs, which vary among soil groups and regions.

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**Table 6** Mean, standard error and ANOVA results for SOC density and CSP of different land-use types

Land-use type	SOC density (t C ha <sup>-1</sup> )	CSP (t C ha <sup>-1</sup> )
Arable land	35.03±2.29 a	96.02±5.06 a
Forestland	51.30±4.38 a	67.73±7.10 b
Grassland	53.34±5.03 a	41.23±5.19 b
Shrub-grass land	60.54±7.51 a	47.05±11.19 b

Data are means±standard error. Different letters indicate statistically significant differences between land use types at *P*<0.05. The same as below.

**Table 7** Mean, standard error and ANOVA results for SOC density and CSP of different soil textures

Soil texture	SOC density (t C ha <sup>-1</sup> )	CSP (t C ha <sup>-1</sup> )
Loamy sand	29.52±12.39 c	24.33±9.61 b
Silt loam	45.66±15.53 ab	100.76±37.63 a
Loam	51.47±17.56 a	64.92±19.36 ab
Clay loam	41.75±11.99 b	93.76±27.64 a
Silt-clay loam	40.01±18.29 b	115.54±32.43 a
Sandy loam	42.38±17.40 b	49.49±11.50 b

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